

IF VISUAL WATER CLARITY IS THE ISSUE, THEN WHY NOT MEASURE IT?

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Abstract

Much water quality monitoring involves measuring suspended solids concentration (SSC). However, the impact of SS is often related to its light attenuation, which reduces visual water clarity and light available for photosynthesis. Thus, measurement of the optical attributes of the suspensoids is often more relevant than SSC.

Nephelometric turbidity, an index of light scattering by suspensoids, is widely used as a simple and cheap, instrumental surrogate for SSC. Turbidity may relate more directly than mass concentration to optical effects of suspended matter. But turbidity is only a relative measure of light scattering (versus arbitrary standards), albeit a useful quantity where a relative index of water cloudiness is sufficient. Turbidity has no intrinsic environmental relevance until calibrated to a 'proper' scientific quantity. Worse, owing to different optical design, different turbidimeters may give very different responses on the *same* samples.

Visual water clarity (measured as Secchi or black disc visibility) is a preferred optical quantity to turbidity, and one with immediate environmental relevance to aesthetics, contact recreation and fish habitat. Contrary to common perception, visual clarity measurement is not particularly subjective, and is more precise than turbidity measurement. Visual clarity measured as horizontal black disc visibility is inter-convertible with beam attenuation, a fundamental optical quantity that can be monitored continuously by beam transmissometry.

This paper discusses the merits of *in situ* visual water clarity measurement over alternative measures. We emphasize the black disk method—a simple, quick, and cheap measurement, yielding real time information that can provide a valuable on-site guide to sampling in water quality monitoring work. Black disc visibility has the great merit of being readily understood by lay people.

We believe that visual water clarity (or, equivalently, beam attenuation) should supplant nephelometric turbidity in many water quality applications, including environmental standards.

INTRODUCTION

Suspended sediment is a ubiquitous water pollutant, with a multitude of environmental impacts on water bodies, including transport of other pollutants such as sorbed nutrients and toxic materials. Effects on aquatic organisms include benthic smothering once sediment settles out of the water column. Water supplies contaminated with suspended sediment may require costly treatment. However, the most visually obvious and perhaps the most ecologically significant, impact of *suspended* sediment is optical—increased light attenuation through water.

Light attenuation by suspended particles in water has two main types of environmental impact: reduced penetration into water of light for photosynthesis and reduced visual range of sighted animals and people. This paper will focus the reduction of visual range, which is more simply related to suspended sediment concentration than is light penetration.

Suspended particles usually dominate light attenuation in natural waters. Waters with high concentrations of fine suspended sediment are described as ‘turbid’ (meaning cloudy), and inevitably these waters are of low visual clarity.

Turbidity is commonly measured in water quality laboratories using a nephelometer, an instrument that detects side scattering of light by a water sample. Nephelometric turbidity is often used as a rough index of the fine suspended sediment content of the water. Turbidity is also commonly (and uncritically) taken as a rough index of water clarity, although published relationships between measures of clarity and turbidity seem rare (Davies-Colley *et al.*, 1993). “Standard Methods” (APHA, 1998) devotes an introductory paragraph in Nephelometric Turbidity Method 2130 to justifying turbidity measurement in terms of water clarity, but no attempt is made to quantitatively *interpret* turbidity in terms of clarity!

We believe that the concepts of turbidity and water clarity, and their relation to suspended sediment concentration (SSC) in water, are poorly understood. In water quality and related fields (e.g., fisheries management), measurements of SSC continue to be made when the main concern is optical (e.g., fish vision) and it would seem more appropriate to make optical measurements, such as turbidity (Lloyd *et al.*, 1987) or water clarity. Furthermore, measurements of turbidity continue to be made in isolation without recognition that this (relative) measure is of little environmental value until cross-calibrated to an absolute quantity such as SSC or clarity. And this is necessary at *each* site of interest because no universal relationship between the variables exists.

In this paper we compare SSC, turbidity, and visual clarity as regards costs, precision, environmental relevance, and other attributes. We recommend wider adoption of simple, but powerful, methods (including instrumental methods) for measuring visual clarity of waters, because of their distinct advantages over the traditional water quality assays of SSC and turbidity especially where optical effects of SS are of particular concern.

This paper is based on a recent review on the topic (Davies-Colley and Smith 2001)

WATER CLARITY AND WATER OPTICS

There are two main aspects of water clarity that concern water managers: *light penetration* and *visual clarity* (e.g., Davies-Colley and Vant, 1988; Davies-Colley *et al.*, 1993). These two very different aspects are both strongly affected by suspended matter in water and both are related to the fundamental optical properties (light *absorption* and *scattering*) of water, but in different ways, hence the need to make the distinction.

The total light attenuation by both absorption and scattering is quantified by the *beam attenuation coefficient*, c (Kirk, 1994). This is simply the sum of the absorption coefficient, a , and scattering coefficient, b :

$$c = a + b.$$

The beam attenuation coefficient is the most easily measured of the inherent optical properties (Kirk, 1994), and the only one that can be measured routinely. The quantities a , b , and c are known as ‘inherent’ optical properties because they are properties only of the water itself and do not depend on the incident light field.

Light penetration is more difficult to measure than visual clarity and is more indirectly and complexly related to a and b than is visual clarity (which is inversely proportional to c). No universal relationship of light penetration to SSC or, for that matter, to turbidity or visual clarity exists. The relationship between light penetration and SSC or its surrogates must be established empirically in a given water body.

The remainder of this paper emphasizes *visual* water clarity, which is probably less well understood than light penetration, despite being of approximately equivalent environmental importance and even more closely related to SSC.

VISUAL WATER CLARITY

Visual water clarity has been traditionally measured using a Secchi disk, a white or black-and-white disk that is lowered into water until the image is judged to disappear from view (e.g., Tyler, 1968). The depth of disappearance, the Secchi depth, is a useful index of *visual* water clarity. Secchi measurement protocols have not been satisfactorily standardized, although recommendations have recently been made (Smith and Hoover, 1999; Smith, 2001). Secchi depth is inversely proportional to the sum of the two different light attenuation coefficients of water [Tyler(1968); Preisendorfer (1986)]:

$$z_{SD} = G/(c + K).$$

The coefficient G depends on reflectance of the disk (typically about 75%, authors’ unpublished data) and of the water, but is usually in the range 6–9 (Tyler, 1968). The dependence of the Secchi measurement on an ‘apparent’ [as opposed to ‘inherent’—see Davies-Colley *et al.* (1993)] property (K , the diffuse attenuation coefficient) shows that Secchi depth is itself an ‘apparent’ optical property that is somewhat dependent on lighting conditions.

A better measure of visual water clarity is the *hydrological range*, the maximum sighting distance of a perfectly black target, viewed horizontally (Duntley, 1962, 1963)—see Figure 1. The black disc ideally reflects no light and so is seen as a silhouette against the light scattered from within the water. Theoretically, the hydrological range is a preferred measure of visual clarity over Secchi depth, because it depends only on the beam attenuation coefficient, c . Davies-Colley (1988) has shown that c (measured at 550 nm near the peak sensitivity of the human eye) can be estimated with reasonable precision from horizontal observations of the visual range of a matte black disk (Figure 1), with the simple empirical equation:

$$y_{BD} = 4.8/c.$$

This inverse relationship of hydrological range (aka ‘black disc visibility’, ‘visibility’, visual clarity) and the beam attenuation coefficient is intuitive and is extremely useful because it permits modeling of visual clarity of water, making use of the conservative property of c (Davies-Colley *et al.*, 1993).

Black disc visibility has three important advantages over Secchi depth as an index of visual clarity (Davies-Colley *et al.*, 1993). Firstly, because the black target (ideally) reflects no light, black disc visibility is independent of ambient lighting. (The Secchi depth, by contrast, varies weakly with light conditions.) Second, y_{BD} yields a valuable, reasonably accurate, estimate of the beam attenuation coefficient, c . Finally, the black disc is observed horizontally and so is useful in very shallow and clear waters such as rivers and littoral waters used for bathing.

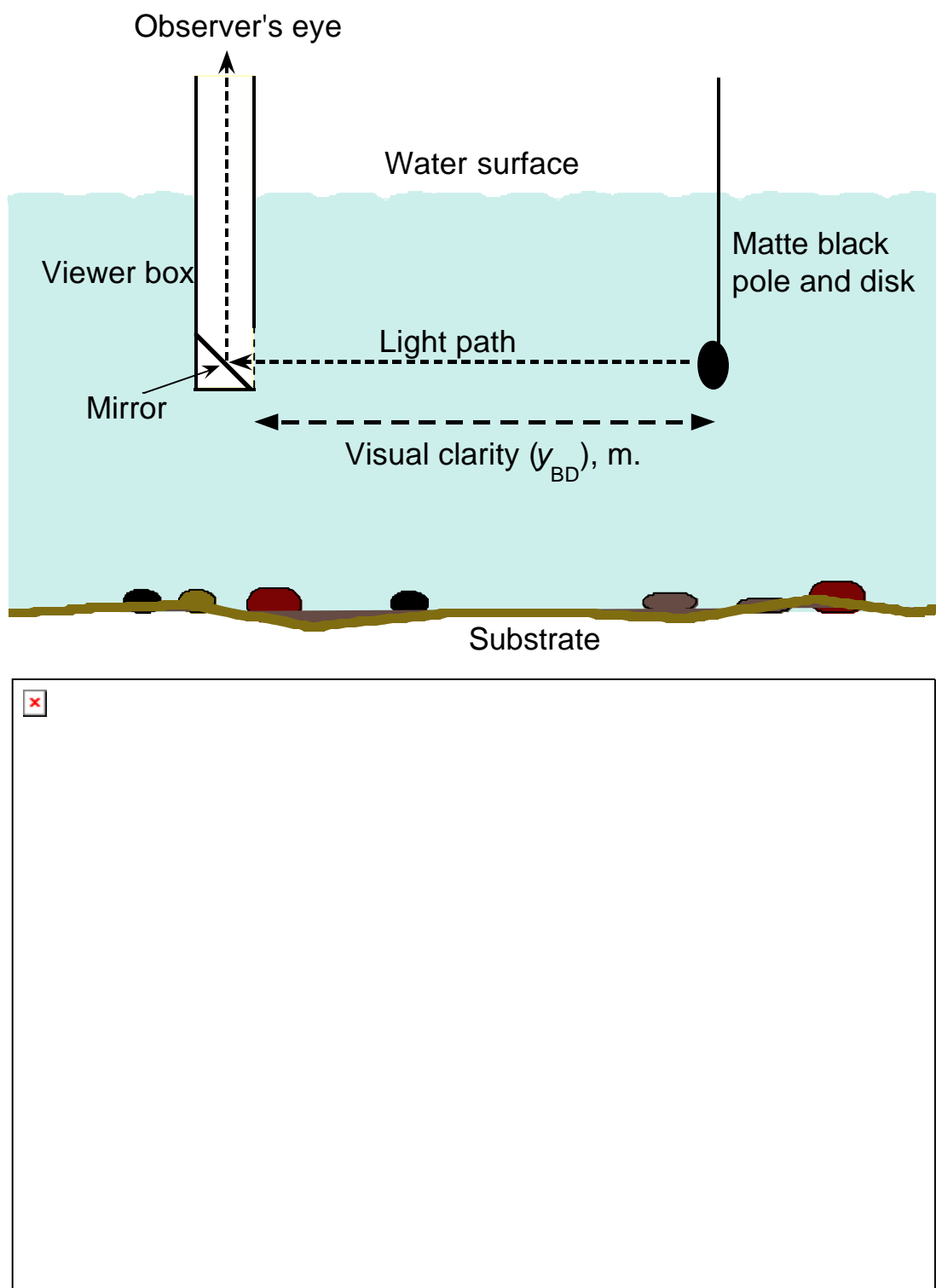


Figure 1. Measurement of black disc visibility, as a schematic and photograph in the Stonehill River, New York, by staff of the New York City Department of Environmental Protection.

We have recommended that horizontal black body visibility (hydrological range), and, equivalently, the beam attenuation coefficient, be taken as the standard measures of visual water clarity (Davies-Colley & Smith 2001).

TURBIDITY

Turbidity is a measure of the ‘cloudiness’ of water related to the light scattering of suspended particles. Because light scattering is difficult to measure directly, turbidity is usually measured by nephelometry—the relative measurement of light scattering through a restricted range of angles to the incident light beam. Typically, nephelometers measure side scattering at angles centred on 90°. Side scattering is in roughly constant ratio to total scattering and nephelometric turbidity has been found to numerically correlate fairly closely with the scattering coefficient, b (e.g., Effler, 1988).

Turbidity measured by different nephelometers has been reported to produce different numerical NTU values (McGirr, 1974) because of differences in optical design of nephelometers even when the different instruments are all calibrated to formazin. For this reason *the instrument used for turbidity measurements should always be specified*. More recently, Davies-Colley & Smith (2001) reported turbidity measurements on 77 New Zealand rivers on two laboratory bench nephelometers: a ‘traditional’ Hach 2100A and its more modern replacement, a Hach 2100AN, to differ by 30% on average over a 3 order of magnitude range.

We emphasise that nephelometric turbidity is merely a *relative* index of side scattering of light referred to side scattering of an *arbitrary* standard (formazin). That is to say, turbidity is not a ‘proper’ scientific quantity, which may be defined for the present purpose as a quantity whose units are reducible to mass-length-time-charge. Despite this, turbidity is often treated as if it were an absolute scientific quantity, in water quality and related fields. Turbidity cannot be converted to scientific units of scattering at 90° (Austin, 1973).

INTER-RELATIONSHIPS BETWEEN TURBIDITY, SSC, AND VISUAL CLARITY

Broad correlations between the three variables turbidity, SSC, and visual clarity exist. For example, Figure 2 shows the inter-relationships between these variables in a wide range of New Zealand rivers at baseflow (Davies-Colley and Close, 1990). All three variables are reasonably closely correlated, although the two optical variables are more closely related to each other (Figure 2B) than either is to SSC (Figures 2A,C).

In waters with a limited range of particle characteristics, the mutual correlation of visual clarity, turbidity and suspended sediment may be appreciably closer. For instance, there is a very close (numerically nearly 1:1) relationship between turbidity and SSC over greater than two orders of magnitude of SSC for samples taken during storm events in New York State's Esopus Creek (Figure 3). In this instance the suspensoids are composed of fairly uniform clay material which is distributed throughout the catchment.

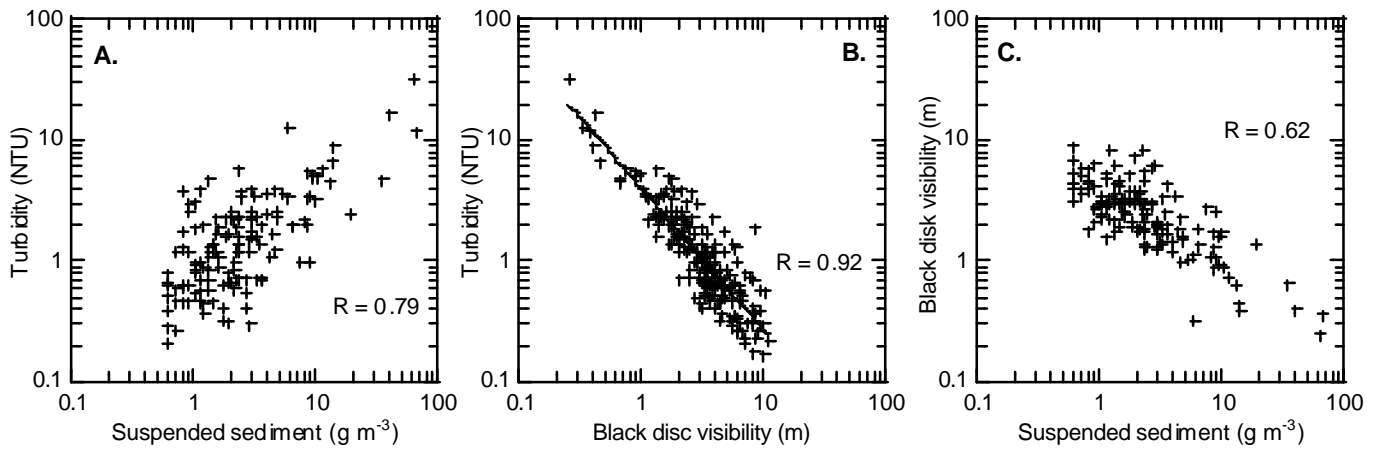


Figure 2. Mutual relationships of visual clarity, turbidity (Hach 2100A) and suspended sediment concentration in 97 New Zealand rivers (each river site sampled up to three times— $n = 274$ in total). Panel A. turbidity versus suspended sediment, B. turbidity versus black disc visibility, C. black disc visibility versus SSC. (Figure 3 of Davies-Colley and Close, 1990—used with permission)

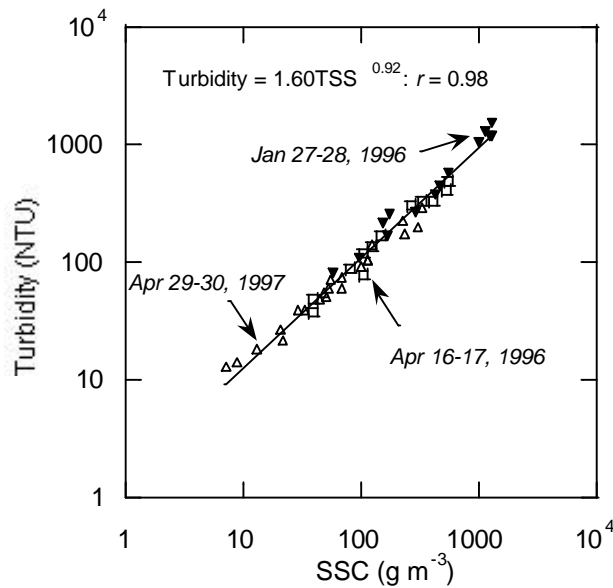


Figure 3. The relationship between nephelometric turbidity (Hach 2100AN) and SSC relationship for three storm events, Esopus Creek, NY (NYC DEP data).

Where SSC really is the concern, for example where estimates of suspended matter yield are required, then such correlations may be very useful. But if *optical effect* of suspended sediment is the concern then there seems little point in attempting to estimate SSC.

A close relationship is sometimes found between turbidity and visual clarity in *particular waters* with dominance of light attenuation by particles of rather similar optical character. By way of example, Figure 4 graphs data for turbidity and black disc visibility in the Esopus and Schoharie watersheds in New York which contain widespread clay-rich glacial deposits. The data are plotted on both linear and logarithmic grids to emphasise the inverse relationship between the two optical variables. Again we have an imperfect inverse relationship between visibility and turbidity, despite very good overall correlation.

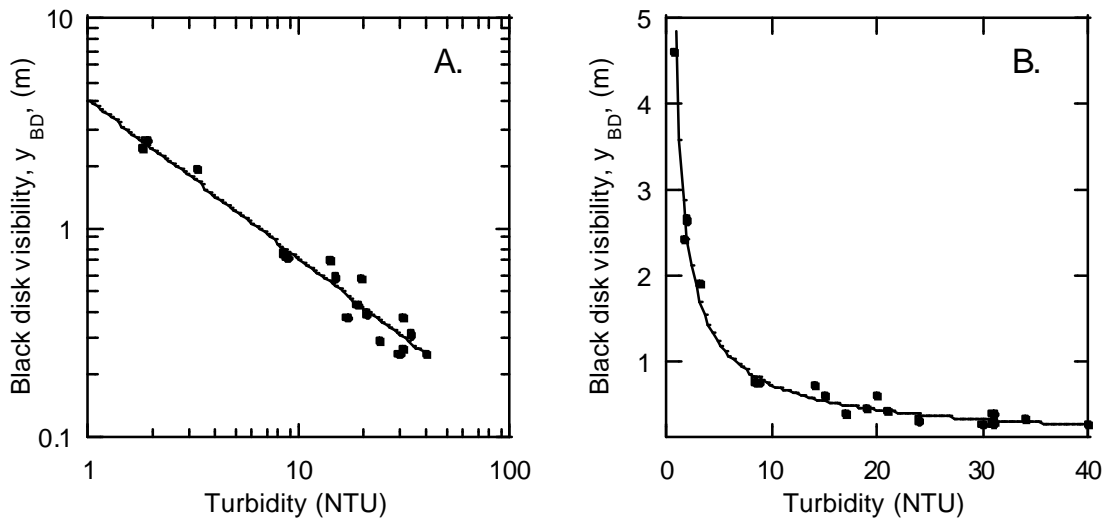


Figure 4. Black disc visibility versus turbidity (Hach 2100AN nephelometer) for 16 sites in the Esopus and Schoharie catchments, in the Catskill region of New York (New York City Department of Environmental Protection, unpublished data). A. Logarithmic scales, B. *Same* data on linear scales. The data are well fitted ($r = 0.995$) by a power law: $y_{BD} = 4.09T^{-0.76}$.

SSC AND TURBIDITY COMPARED WITH VISUAL CLARITY

Table 1 compares and contrasts the traditional water quality measures, SSC and nephelometric turbidity, with visual water clarity. It will be surprising to some readers that visual clarity, an apparently subjective measure involving use of the human eye, is more precise ($\pm 4\%$) than turbidity or SSC ($\pm 10\%$), as well as being cheaper, and yielding data on site and in “real time”. Furthermore, visibility is a true scientific measurement that requires no calibration—unlike relative and arbitrary turbidity measurement by nephelometry. Perhaps most important of the attributes considered in Table 1 is the *environmental relevance* of the different measures.

Suspended mass concentration, and thus mass load (concentration \times flow), is highly relevant to studies of sediment yield in geomorphology and related fields, and to concerns with effects of sediment once settled. But while sediment remains suspended optical measures are often more environmentally relevant than SSC.

Turbidity, although an optical measurement, is not immediately relevant to environmental problems because it is a relative and arbitrary measurement—even though turbidity is often treated as though it were an absolute scientific quantity (McCarthy *et al.*, 1974). To be really useful, turbidity measurements must be *calibrated* (e.g., to SSC or to visual clarity) depending on whether the main concern is mass concentration of suspended sediment or its optical effect.

Visual clarity is more environmentally relevant than turbidity because it is a *direct* measure of an optical attribute of water that strongly affects aquatic habitat and human use of waters. For instance, a number of studies of reactive distance of predator fish have characterized the test water in terms of turbidity (Abrahams and Kattenfeld, 1997), which fails to recognize that visual range in the water is an upper bound to, and ultimately controls, reactive distance.

We consider that nephelometric turbidity is unsuitable for *environmental standards* because it is not an absolute, scientific measurement, and is imperfectly related to the attribute of water that it purports to indicate, namely visual clarity. Nor is SSC a suitable measure for standards where the environmental effects of suspended matter are related to its light attenuation rather than to its mass concentration.

CONCLUSIONS

When the optical effect of suspended sediment is of primary concern, light penetration or visual water clarity are generally the most appropriate measures. Visual water clarity is a true scientific measurement that is not particularly subjective and can be measured with appreciably better precision than either turbidity or SSC.

Turbidity measurement may be appropriate where a relative index of water cloudiness is sufficient, or if there is some inherent advantage of a laboratory assay. However, to be meaningful, turbidity needs to be calibrated to a proper scientific quantity. Visual water clarity measurement has most of the advantages of turbidity, but is a preferred optical measurement, being a true scientific quantity that can be measured with better precision and even more cheaply, and has immediate environmental relevance. Visual water clarity measurement deserves to become far more prevalent in water quality and related fields—preferably measured as hydrological range (= black body visibility) and supported by continuous measurement, not of arbitrary nephelometric turbidity, but of beam attenuation, an inherent optical property of water.

Generally SSC is not an appropriate measure for environmental standards where the environmental effects of suspended matter are related to its light attenuation rather than to its mass concentration. Nephelometric turbidity, which is not a proper scientific measurement, is not entirely suitable either. We recommend formulation of environmental water quality standards in terms of visual water clarity, recognizing its environmental relevance and significant practical advantages over both SSC and turbidity.

TABLE 1. Comparison of suspended sediment concentration, nephelometric turbidity, and visual clarity measurement for water quality assessment.

Attribute	Suspended sediment concentration (SSC)	Turbidity	Visual water clarity (or, alternatively, beam attenuation coefficient)
Principle and Procedure	Weight of filtered particulates	Side scattering of light by nephelometry (relative scale)	Horizontally sighting range of a black disc (or Secchi depth) (alternatively, beam transmittance measurement)
Equipment	Filter assembly with vacuum pump, oven, weigh balance, desiccator, glass fiber filters	Nephelometer and standards	Underwater viewer and visual target, tape measure. (beam transmissometer)
Calibration?	None	Arbitrary calibration to formazin	None
Scientific measurement? (units)	Yes (g m^{-3})	No, arbitrary, relative measurement (in NTU)	Yes (m) (Beam attenuation coeff., m^{-1})
Cost (and difficulty)	\$23/sample Simple, but expensive	Fairly simple \$5/sample	Simple \$4/observation ¹
Precision (typical standard error)	10% ²	10% ³	4% ^{4,5}
Sample size (and storage)	100 mg residue ⁶ Samples fairly stable if chilled, dark	<100 mL (laboratory) Samples unstable, keep chilled, dark, measure < 24 hr	Not applicable (usually done <i>in situ</i>)
On site or <i>in situ</i> measurement?	No (must be done in a laboratory)	Yes (portable models)	Yes (usual procedure)
Continuous monitoring?	No	Yes (<i>in situ</i> turbidity monitors)	Yes, as beam transmittance (from which visibility may be calculated)
Environmental relevance	Relevant to sediment yields (in geomorphology, agronomy), and benthic effects of sedimentation. Less relevant to optical effects.	<i>Indirectly</i> relevant - because the measurement is <i>relative</i> to <i>arbitrary</i> standards. Requires calibration (e.g., to suspended solids or visual clarity)	Relevant to aesthetic quality of water and habitat for sighted aquatic animals. Less relevant to sediment mass-related impacts

1. Assuming 10 minutes *extra* on site per observation (at \$20/hr), and allowing \$0.60/observation for equipment depreciation.
2. McGirr (1974), APHA (1998)
3. McGirr (1974), ASTM (1996), EPA (1999)
4. Davies-Colley and Close (1990)
5. Smith and Hoover (1999)
6. Sample volume depends on sediment concentration, for instance, 10L is needed to provide 100 mg residue at 10 g m^{-3} .

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